Carbon Dioxide Emissions Mitigation Strategy through Enhanced Geothermal Systems: Western Anatolia, Turkey

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Abstract

Although Turkey is not the biggest GHG polluter, its emissions have increased by 110.4 % since 1990. Currently, its CO₂ emissions alone have crossed 400 Mt. Within the scope of 2 °C targets (2D scenario), the country can easily surpass this target test by increasing its renewable energy sources as a primary energy source mix, by developing its Enhanced Geothermal Sources (EGS) locked up in the radiogenic granites of western Anatolia. The radiogenic heat generated by these granites, spread over an area of 4221 sq. km, varies from 5.3 to 16.34 $\mu\text{W}/\text{m}^3$. Based on the electricity generation capacity of granites from Soultz-sous-Forêts and Cooper Basin EGS sites, the combined electricity generation capacity of Kestanbol and Kozak granite plutons is about 830 billion kWh. For the period extending from 2019 to 2023, Turkey is aiming at reducing the usage of gas for electricity generation from 29.9 to 20.7%, increasing the share of renewable energy sources from 32.5 to 38.8%, increasing the electricity production from local energy sources from 150 TWh to 219 TWh and increasing the electricity usage per-capita from 3.7 to 4.3 MWh. These energy targets can be achieved by major contributions from hydrothermal and EGS energy sources. This review demonstrates that besides electricity and heat, EGS energy can be utilized, together with other renewable energy sources like hydrothermal, wind, and concentrated solar for providing fresh water through the desalination process. These energy sources would provide food, energy, and water security to the country for several decades.

Keywords: Enhanced Geothermal Source, CO₂ emissions, climate change, Carbon trade, renewable energy, desalination, food security.

1. Introduction

Turkey, with an area of 785350 km², and a population of 84 million, is one of the largest countries in Europe and the Middle East. Turkey's greenhouse gases (GHG) emissions in 2013 were 0.94 % of the global emissions. Although Turkey is not the biggest GHG polluter, its emissions have increased by 110.4 % since 1990. Currently, its CO₂ emissions alone have crossed 400 Mt. Within the scope of 2 °C targets (2D scenario, IEA, 2014), the country can easily surpass this target test by increasing its renewable energy sources as a primary energy source mix, especially the geothermal energy. The country need not drastically change its

energy policy except emphasizing the development of new geothermal energy sources like the Enhanced Geothermal Systems (EGS) that are available in large amounts locked up in the granites. The development of these energy sources will offset gas imports and thus have an enormous influence on the country's macro-economic and Gross Domestic Product (GDP). Turkey, located within the Mediterranean basin that is very susceptible to climate change will significantly impact temperature rise, water resources situations, rainfall pattern changes, droughts, and sea-level changes. Turkey has already experienced a rise in temperatures over the past 42 years (Yelden and Voyvoda, 2015), especially during the summer season. To a large extent, these factors will impact the coastal regions of Turkey, especially those located along the Aegean Sea. It is estimated that a one-meter rise in sea level will affect nearly 3 million populations in Turkey (Yelden and Voyvoda, 2015).

Primary energy that can substitute the fossil fuels energy sources should generate base-load electricity and have a low carbon footprint with maximum efficiency. Even if Turkey can lower the carbon intensity curve between 2D and 4D (from 98 to 95, circle in **Figure 1**), this will lower the climate-related effects to a lag extent.

Figure 1. Carbon intensity index showing the influence of renewables in the modified 2D and the 4D scenarios (modified after IEA, 2014).

All the 195 countries under the CoP (Convention of Parties), as agreed during the Paris 2015 CoP conference, are not able to commit to reducing the use of fossil fuels as primary fuels

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4 64 and reduce CO₂ emissions because these countries are not able to find robust alternate energy
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6 65 sources that can generate base-load electricity and work with an efficiency of 80% and above
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8 66 with zero carbon or low carbon footprint. Although during the Covid-19 pandemic, CO₂
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10 67 emissions declined by about 5.8% globally in 2020, emissions started rising drastically in late
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12 68 December 2020, and it is estimated to cross 33 gigatons of CO₂ in 2021, registering a 1.2%
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14 69 lower than the level of 2019 (IEA, 2021a, b). However, technological advancement is
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16 70 creating hope to meet 2D or 4D scenarios by 2030. This hope will become a reality only
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18 71 when the usage of fossil fuels shows a decline. According to the Energy Sector Carbon
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20 72 Intensity Index (Carbon intensity index of energy production is measured as the quantity of
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22 73 carbon dioxide emitted per unit of energy production. This is measured in kilograms of CO₂
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24 74 per kilowatt-hour), if the countries follow business as a usual model (BUM), then the world is
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26 75 heading towards disaster (IEA, 2014). But electricity generation through renewable energy
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28 76 sources is on track by many countries and making convincing progress, including Turkey,
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30 77 thus creating a hope to bend the CO₂ emissions curve by 2050 (see Figure 1).
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36 78 Although Turkey has large hydrothermal resources, generating about 1576 MWe from 346
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38 79 known geothermal fields, its full potential of 4000 MWe is yet to be exploited (Baba et al.,
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40 80 2020). Besides the hydrothermal source, Turkey has large high heat generating granites
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42 81 spread over the entire country, and most of them are located in the western part of Anatolia.
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44 82 There is a large amount of energy locked up in these granites that need to be explored and
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46 83 exploited. Within the scope of this study, the energy potential that can be obtained from
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48 84 granites and its contribution to both the economy and climate change were evaluated in this
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50 85 study.
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2. Energy Consumption

Turkey is consuming about 384 billion kWh of electricity per year (the year 2020, from fossil fuels alone) with per-capita energy consumption of about 4659 kWh (Diddglio et al, 2020; IEA, 2021c). Over the last decade, the primary source of energy supply to Turkey is mainly from fossil fuels, and they will continue to contribute to the primary energy source for the next decade (**Table 1**).

Table 1 Primary energy sources in Turkey (adapted from Keles and Bilgen, 2012, Diddglio et al., 2020).

	2008	2010	2020	2030
Fossil fuels (Mtoe)	18.58	27.45	32.99	35.4
Nuclear			7.3	14.6
Hydro	3.66	5.34	10	10
Geothermal	0.74	0.98	1.71	3.64
Biomass	5.1	5.12	4.96	4.64
Solar and wind	0.78	1.05	2.27	4.28
Total production	28.86	39.94	59.23	72.56

The energy consumption by Turkey from all the energy sources (Table 1) is growing as the demand is surging due to population growth of 1.4 % annually. This energy demand is expected to grow beyond 70 Mtoe in the coming decade (Table 1, **Figure 2**) supported by hydropower which is projected to increase by twice the reported value (116300 GWh) in Table 1, to 208488 GWh by the year 2023 itself (IEA, 2021c). Thus, more than half of the energy supply to Turkey is supported by imported fossil fuels, while the country has significant potential to offset fossil fuels with geothermal energy sources and reduce fuels imports, CO₂ emissions and increase its GDP. In 2020 Turkey's gas consumption was 48 billion m³ while it imported 44.2 billion m³ of gas. In the first quarter of 2021, gas imports to Turkey from Russia have increased by 18% year on year y-o-y basis (IEA, 2021c). According

to IEA (2021a), demand for natural gas is set to rebound in 2021, and the demand will keep rising over the next decade, defeating the 2D goal set by the IPCC (2018) unless countries. This indicates that Turkey has to push the renewable sector hard to achieve the target of 2D set by the IPCC (2018). The average household gas consumption in Turkey is about 1000 m³ in 2020, and the annual amount paid by the household gas consumer is about 2000 TL (about 200 Euro). There is scope to offset household gas consumption by geothermal energy (heat) and reduce CO₂ emissions and reduce the consumer cost of energy below this amount (Worldmeters, 2021).

Figure 2. Energy demand by Turkey

To achieve sustainable economic growth, efficient and diversified energy sources (renewable and non-renewable sources) are essential. Also, the cost of renewable energy sources (RES) should be affordable by the country. In this context, there is a great opportunity for the country to promote renewable energy, especially geothermal energy because it has a significant geographical location in terms of its renewable energy capacity. Besides, Turkey can use almost all known renewable energy sources, such as solar, wind, geothermal, hydro, wave, and biomass. Today, renewable sources compose almost 48 percent of the whole

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4 141 energy-producing capacity in Turkey, with hydropower topping the renewable energy list.
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6 142 Energy generation with renewable sources is increasing globally. By the year 2030, Turkey's
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8 143 energy demand is expected to increase from the current 60 Mtoe to 100 Mtoe (Figure 2) in
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10 144 another decade, a nearly 100 percent increase. To comply with the country's 2023 vision, the
11
12 145 Ministry of Energy and National Resources (MENR) encouraging the share of renewable
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14 146 energy resources in the primary energy source mix by augmenting the renewable energy
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16 147 source share to 61000 MW by 2023 with a major contribution of 34000 MW from
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18 148 hydropower, 20000 MW from wind, 1000 MW from geothermal, 5000 MW from solar and
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20 149 1000 MW from biomass sources (WECTNC, 2009, Erdin and Ozkaya, 2019, Diddglio et al.,
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22 150 2020).
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26 151 To mitigate CO₂ emissions and sustain growth in GDP, Turkey has two options to adapt
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28 152 (Diddglio et al., 2020) one is the Reference Scenario (RS) and the other the Alternative
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30 153 Scenario (AS). In the RS the electricity demand will grow by 93%. Diddglio et. al (2020)
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32 154 forecasts that the electricity demand will increase 93% under RS by 2040 but AS may restrict
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34 155 this growth to only 64%. What Turkey needs is a technology-driven transformation in all
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36 156 energy sectors under AS to achieve the desired target compatible with 2D or 4D scenario of
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38 157 IEA (2014). This needs an annual budget of US\$ 9 billion for the energy sector. This amount
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40 158 is 10% more than what is anticipated under RS. But in the case of RS (similar to BAU
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42 159 scenario of IEA, 2014), more expenditure will be incurred to mitigate CO₂ emissions, like
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44 160 paying a carbon tax or buying carbon credits from countries emitting low carbon emissions.
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46 161 For example, under the RS, Turkey will be emitting 30% more CO₂ in 2040 compared to that
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48 162 emitted in 2019, while it is only 10% under the AS during the same projected period
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50 163 (Diddglio et al., 2020). This means the carbon intensity of the power sector drops by 28%
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52 164 under RS while it drops by 54% under AS (Figure 1), bending the carbon intensity curve
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54 165 between 2D and 4D curves (Figure 1). It is projected that AS will reduce much higher CO₂
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emissions after 2040 due to reduced oil and gas imports and an increase in higher primary energy contribution (33%) from renewable energy sources (Diddglio et al., 2020).

3. CO₂ emissions by Turkey and strategy to reduce emissions

Turkey has increased its CO₂ emissions by about 110 % since 2000 and is projected to cross 500 Mt in the next decade from electricity generation alone (Figure 3) (Yelden and Voyvoda, 2015; Ritchie and Roser, 2020).

Figure 3. CO₂ emissions by Turkey (Emissions from the cement industry are not included. <https://www.worlddata.info/asia/turkey/energy-consumption.php> (accessed on 24 June 2021).

The per capita emissions of CO₂ increased to 4.5 tons from 3 tons during the past ten years due to annual population growth of about 1.4% (Ritchie and Roser, 2021). Major contributors to CO₂ emissions are electricity and heat, followed by transport (Figure 4). Industry emissions here exclude the cement industry. If CO₂ emissions from the cement industry are included, then the CO₂ emissions will surpass 8 billion tons by 2030 (Ritchie and Roser, 2021). Turkey, being a major producer of cement, with an annual turnover of 84 Mt of clinker, consumes about 8 million MWh of electricity from fossil fuels with emissions of

Figure 4. CO₂ emissions from different sectors (Ritchie and Roser, 2021)

The tourism industry also contributes considerable CO₂ emissions due to the high influx of tourists and increased energy-related gadgets and transport (Eyuboglu and Uzar, 2019). Turkey being ranked on the top ten tourists destinations, the percentage of tourists visiting Turkey has registered a huge increase of over 400% from 2000 till last year (Eyuboglu and Uzar, 2019). The annual influx of tourists to Turkey is about 30 million (Katircioglu, 2014). According to The World Travel and Tourism Council (WTTC) (2018), in the year 2017, Turkey's tourism sector contributed about 32 billion US\$ directly to the country's economy, contributing 3.8% to the GDP. But the CO₂ emissions from tourism alone is about 135 million tons (Katircioglu, 2014; WTTC, 2018).

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4 223 It has been suggested that to meet the 2D scenario strategy by reducing CO₂ emissions from
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6 224 the present 500 Mt to 390 Mt, Turkey should implement three important policy instruments
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8 225 (Yelden and Voyvoda, 2015). They are 1) imposing a carbon tax, 2) investment in
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10 226 renewables from the carbon tax, and 3) technological advancement to adopt energy
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12 227 efficiency. Although the implementation of the carbon tax may take a longer time, the
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14 228 remaining two policy instruments can be adopted by promoting geothermal energy resources,
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16 229 both hydrothermal and Enhanced Geothermal Systems, since the infrastructure to augment
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18 230 the geothermal resources (power and heat) is already in place along the western Anatolian
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20 231 region and as mentioned above Turkey is currently generating CO₂ emission free electricity
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22 232 1576 MWe from hydrothermal resources. In the subsequent sections it is shown how Turkey
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24 233 can further reduce emissions by developing EGS resources.
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234 235 **4. Geothermal energy resources of Turkey** 236

237 Turkey made phenomenal progress in establishing strong geothermal power for ten years, by
238 increasing the installed capacity of 94 MWe in 2010 to 1576 MWe in 2020 (**Figure 5**),
239 registering 157% annual growth. It is projected that by 2030 greater than 3000 MWe
240 electricity will be added to the main electricity grid by geothermal power plants (Table 1).
241 The estimated installed capacity of geothermal power (from hydrothermal sources) is about
242 4000 MWe (Baba et al 2021; Mertoglu, et al., 2020).
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Figure 5. The installed capacity of geothermal power in 2020 (adapted from Baba et al., 2021).

This energy is from hydrothermal sources, distributed in about 346 geothermal fields in 63 provinces (**Figure 6**).

Figure 6. Map showing the location of the geothermal provinces of Turkey and thermal manifestations (small black circles) within the provinces (adapted from Akkuş et al., 2019; MTA, 2019).

However, the country has huge Enhanced Geothermal Systems (EGS) resources locked up in its high heat generating granites (Chandrasekharam and Baba, 2021). If the full potential is

exploited from hydrothermal sources (4000 MWe, Baba et al., 2021), to generate electricity, hydrothermal energy alone can reduce CO₂ emissions of about 32211 million kg from the gas savings. Only 10% of the geothermal fields contain high enthalpy resources and are capable of generating electricity (Baba et al., 2021), and the remaining 90% are low to medium enthalpy resources, best suited for direct applications like space heating and cooling, greenhouse cultivation, and dehydration. Turkey is in the top five countries utilizing 3488 MWt of geothermal energy for direct applications (Lund and Toth, 2020), with major applications being in space heating and air conditioning. These two applications use about 1453 MWt annually (Lund and Toth, 2021; Mertoglu et al., 2020; Baba et al., 2021). This energy is just 1/6 the of the total potential of 20000 MWt estimated from all the geothermal provinces of Turkey (Baba et al., 2021; Mertoglu et al., 2020; Lund and Toth, 2021). Even if half the amount of this potential is developed for district and individual home heating, this will reduce 147 Mt of CO₂ emissions (see Figure 5). The other geothermal sources that are yet to be developed and exploited are Enhanced Geothermal Systems. The potential of EGS in Turkey, especially in the western Anatolian, is huge, and this source is not site-specific like the hydrothermal resources. EGS taps the heat from the high heating granites through a liquid medium (either water or CO₂), and the resulting steam or vapour runs the turbine to generate electricity.

5. EGS sources in Western Anatolia

Enhanced Geothermal Systems (EGS) is a technology where a set of fractures is induced into a hot granite body or a bore hole is drilled into the granite at a certain depth (Figure 7). A single bore-well can generate about 3 to 4 MWe. Heat is extracted through a medium (water or carbon dioxide) for power generation. This technology is being commercialized and, in the future, could unlock several thousands of megawatts of power (Robert, 2012; Letcher, 2020).

Figure 7. Conceptual diagram showing the EGS technology.

For example, the technical potential of the EGS of the US is estimated at 100 GWe. This is 30 times greater than the current installed geothermal power capacity in the US. There are a few successful plants that are being in operation today. The Soultz-sous-Forets EGS plant in France is generating 3 MWe now by extracting heat from granites at 200 °C from a depth of 5 km. Similarly, in Cornwall, UK, the EGS project is near completion and is expected to generate 10 MWe and 55 MWt (Koelbel and Genter, 2017; Letcher, 2020). Such high heat generating granites are common around the Red Sea region, Africa and the Himalayas (Chandrasekharam et al., 2014; 2015, 2016; Lashin et al., 2014; Omenda et al., 2012)

The granites in Turkey contain a high concentration of U, Th, and K and hence generate a considerable amount of heat above the average heat-generating value of 5 $\mu\text{W}/\text{m}^3$ in granites. **Table 2** gives the heat generation and heat flow values of certain important granites exposed in the western Anatolian region. The radioactive heat production (RHP in $\mu\text{W}/\text{m}^3$) by granites

The entire western Anatolian region is characterized by high heat flow and high geothermal gradients. The measured heat flow values from bore wells vary from 50 to 133 mW/m², while measured geothermal gradients vary from 39 to 57 °C/km. In addition, the Curie point depth (CPD) obtained from aeromagnetic anomaly investigations varies from 12 to 19 km along the region bordering the Aegean Sea and western Anatolia. Thus the temperatures of the granitic batholiths in the western Anatolian region range from 170 to 270 °C at 4 km depth (Akin et al., 2014; Karat and Aydın, 2004; Eckstein, 1978; Erkan, 2015). The heat flow values calculated based on the heat content of the granites (**Table 2**) are similar to the values measured from deep bore wells (Erkan, 2015). Based on the results published from the two EGS projects, one in the Soultz Forte in France and the second one in the Cooper Basin, Australia (Koelbel and Genter, 2017; Somverville et al., 1994; Letcher, 2020), and based on the heat flow values and geothermal gradient recorded in the western Anatolian region and considering the heat-generating capacity of the granites of western Anatolia it is presumed that these granite batholiths can generate large amounts of electricity and heat and one km³ of such granite can generate 79 x 10⁶ kWh of electricity for 30 years (Somerville et al., 1994; Cooper et al., 2010; Chandrasekharam et al., 2015).

380 Table 2 gives the heat generation and heat flow value over the granites exposed in the western Anatolian region.

Serial No	Sample location	Sample No.	U (ppm)	Th (ppm)	K (wt %)	RHP ($\mu\text{W}/\text{m}^3$)	HF (mW/m^2)	Reference	280 km ²
1	Eğriöz pluton	AT16	13.80	84.30	4.04	9.75	137.54	Jacob, 2011	
2	Eğriöz pluton	AT20B	9.80	34.30	4.68	5.33	93.30	Jacob, 2011	
3	Kestanebolu pluton	KO41B	7.80	40.50	3.19	5.10	91.04	Black, 2012	219.00
4	Kestanebolu pluton	KO42	10.20	47.70	3.86	6.28	102.82	Black, 2012	
5	Kestanebolu pluton	KO43A	16.20	60.50	3.90	8.71	127.12	Black, 2012	
6	Kestanebol granitoid	1	11.90	50.00	3.74	6.87	108.67	ŞAHİN et al., 2010	
7	Kestanebol granitoid	2	8.20	54.00	3.95	6.21	102.11	ŞAHİN et al., 2010	
8	Kestanebol granitoid	3	8.30	62.00	4.14	6.81	108.08	ŞAHİN et al., 2010	
9	Kestanebol granitoid	4	17.40	80.00	3.98	10.38	143.76	ŞAHİN et al., 2010	
10	Kestanebol granitoid	5	16.10	59.00	3.83	8.58	125.76	ŞAHİN et al., 2010	
11	Kestanebol granitoid	6	14.30	62.00	3.92	8.33	123.29	ŞAHİN et al., 2010	
12	Kestanebol granitoid	7	15.70	61.00	3.76	8.61	126.05	ŞAHİN et al., 2010	
13	Kestanebol granitoid	8	16.30	62.00	4.11	8.86	128.61	ŞAHİN et al., 2010	
14	Kestanebol granitoid	9	15.90	59.00	3.92	8.53	125.33	ŞAHİN et al., 2010	
15	Kestanebol granitoid	10	14.00	62.00	3.91	8.25	122.51	ŞAHİN et al., 2010	
16	Kestanebol granitoid	11	10.70	47.00	3.82	6.36	103.58	ŞAHİN et al., 2010	
17	Kestanebol granitoid	12	11.80	58.00	3.88	7.41	114.07	ŞAHİN et al., 2010	
18	Kestanebol granitoid	13	10.40	42.00	3.76	5.93	99.30	ŞAHİN et al., 2010	
19	Kestanebol granitoid	14	12.60	53.00	3.69	7.25	112.49	ŞAHİN et al., 2010	
20	Kestanebol granitoid	15	17.00	47.00	3.49	7.95	119.47	ŞAHİN et al., 2010	
21	Kestanebol granitoid	16	9.70	47.00	3.38	6.06	100.59	ŞAHİN et al., 2010	
22	Kestanebol granitoid	17	9.60	40.00	3.81	5.59	95.90	ŞAHİN et al., 2010	
23	Kestanebol granitoid	18	7.50	43.00	3.69	5.25	92.47	ŞAHİN et al., 2010	
24	Kestanebol granitoid	19	12.30	65.00	3.70	8.00	120.02	ŞAHİN et al., 2010	
25	Kestanebol granitoid	20	14.10	54.00	3.72	7.71	117.06	ŞAHİN et al., 2010	
26	Kestanebol granitoid	22	11.10	47.00	4.03	6.48	104.80	ŞAHİN et al., 2010	
27	Kestanebol granitoid	29	15.40	59.00	3.77	8.39	123.91	ŞAHİN et al., 2010	
28	Kestanebol granitoid	32	14.30	65.00	3.88	8.53	125.33	ŞAHİN et al., 2010	
29	Kestanebol granitoid	27	9.70	50.00	4.57	6.38	103.78	ŞAHİN et al., 2010	
30	Kestanebol granitoid	61	9.90	40.00	3.76	5.66	96.63	ŞAHİN et al., 2010	
31	Kestanebol granitoid	62	10.80	63.00	3.67	7.48	114.75	ŞAHİN et al., 2010	
32	Eğriöz pluton	1271 (EP)	9.10	51.00	3.25	6.17	101.70	Akay, 2009	
33	Eğriöz pluton	1322 (EP)	30.80	24.90	2.62	9.88	138.84	Akay, 2009	
34	Subvolcanic phases	2	9.50	35.00	3.19	5.16	91.61	Angi et al., 2016	
35	Subvolcanic phases	5	12.10	55.00	4.89	7.37	113.71	Angi et al., 2016	
36	Subvolcanic phases	8	16.10	65.60	3.48	9.00	130.00	Angi et al., 2016	
37	Subvolcanic phases	10	10.30	43.90	3.57	6.02	100.17	Angi et al., 2016	
38	Sahli granitoid	10DEG07	15.60	15.40	3.08	5.36	93.64	Dilek et al., 2009	31.00
39	Sahli granitoid	11DEG07	15.30	14.20	2.48	5.15	91.47	Dilek et al., 2009	
40	Sahli granitoid	27DEG07	20.80	13.00	2.24	6.46	104.56	Dilek et al., 2009	
41	Sahli granitoid	32DEG07	16.10	16.20	2.71	5.51	95.13	Dilek et al., 2009	
42	Sahli granitoid	35DEG07	20.60	14.90	3.40	6.64	106.45	Dilek et al., 2009	
43	Behrekdağ	CS-a	13.00	59.00	6.60	8.04	120.40	Koksal et al., 2004	
44	Cefalikdağ	CS-b	13.00	96.00	5.23	10.47	144.68	Koksal et al., 2004	
45	Celebi	CS-c	30.00	114.00	7.99	16.34	203.41	Koksal et al., 2004	
46	Celebi	CS-d	16.00	121.00	5.54	13.00	169.96	Koksal et al., 2004	
47	Celebi	CS-e	12.00	33.00	7.87	6.10	101.05	Koksal et al., 2004	
48	Kestanebol granitic pluton	G1	29.21	83.84	5.08	13.78	177.80	Orgun et al., 2007	
49	Kestanebol granitic pluton	G2	14.49	53.11	3.84	7.76	117.57	Orgun et al., 2007	
50	Kestanebol granitic pluton	G3	26.52	75.45	4.19	12.43	164.25	Orgun et al., 2007	
51	Kestanebol granitic pluton	G5	12.61	48.34	3.73	6.93	109.33	Orgun et al., 2007	
52	Kestanebol granitic pluton	G6	14.53	51.61	3.96	7.67	116.74	Orgun et al., 2007	
53	Kestanebol granitic pluton	G7	12.08	59.41	4.27	7.61	116.12	Orgun et al., 2007	
54	Kestanebol granitic pluton	G8	14.67	56.65	3.92	8.06	120.55	Orgun et al., 2007	
55	Kestanebol granitic pluton	G9	15.66	33.06	3.88	6.67	106.74	Orgun et al., 2007	
56	Kestanebol granitic pluton	G10	8.20	39.95	3.87	5.23	92.32	Orgun et al., 2007	
57	Kestanebol granitic pluton	G11	11.78	65.26	4.04	7.92	119.18	Orgun et al., 2007	
58	Kestanebol granitic pluton	G12	9.96	34.76	2.39	5.19	91.88	Orgun et al., 2007	
59	Kestanebol granitic pluton	G13	10.64	36.88	2.16	5.49	94.88	Orgun et al., 2007	
60	Kestanebol granitic pluton	G15	11.82	48.61	3.45	6.72	107.22	Orgun et al., 2007	
61	Kestanebol granitic pluton	G16	10.88	44.13	3.04	6.13	101.32	Orgun et al., 2007	
62	Kestanebol granitic pluton	G17	10.85	42.73	3.35	6.06	100.58	Orgun et al., 2007	
63	Kestanebol granitic pluton	G18	17.63	63.71	4.61	9.37	133.67	Orgun et al., 2007	
64	Kestanebol granitic pluton	G19	12.08	27.11	4.17	5.37	93.70	Orgun et al., 2007	
65	Kestanebol granitic pluton	G20	23.84	69.35	4.71	11.36	153.63	Orgun et al., 2007	
84	Kozak pluton	S-65	11.9	34.9	2.9	5.7	97.5	Karacık et al., 2008	
85	Kozak pluton	K-6	13.5	40	2.8	6.5	105.0	Karacık et al., 2008	
86	Kozak pluton	K-7	10.8	40.1	2.9	5.8	98.2	Karacık et al., 2008	
87	Kozak pluton	K-8	11.8	37.8	2.9	5.9	99.2	Karacık et al., 2008	
88	Kozak pluton	ZK-02-16	13.9	51	3.8	7.5	114.6	Karacık et al., 2008	
89	Kozak pluton	ZK-02-23	12.9	40.5	3.9	6.5	104.8	Karacık et al., 2008	

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6. Discussion

Major sources of CO₂ emissions in Turkey are electricity (400 Mt), space heating (147 Mt), cement industry (104 Mt), and tourism (135 Mt). With annual population growth of 1.4 %, the CO₂ contribution due to increase in population in the next decade would be around 50 Mt. The emissions from electricity generation is anticipated to cross 500 Mt (Figure 3) due to energy demand crossing over 70 Mtoe (Figure 2) supported by fossil fuels based electricity supply which Turkey has imported nearly 45000 million m³ of gas (Ceicdata, 2021) and gas imports are going to increase by about 18 % (IEA, 2021c) to meet the energy demand and maintain sustainable economic growth. This indicates that the country is adopting the RS outlook in the electricity growth pattern (Diddglio et al., 2020) and allowing emissions to cross 500 Mt by the year 2030. However, the country can still maintain sustainable economic growth under the Alternate Scenario (AS) by developing its untapped energy from high heat generating granites. Already the country's hydrothermal source is providing 1.71 Mtoe of clean energy and is expected to double the production by 2030 (Table 1). Currently, Turkey has utilized only 1576 MWe from its 4000 MWe of available hydrothermal sources (Baba et al., 2021). By utilizing its remaining 3424 MWe of energy from the hydrothermal sources, the country can save about 24 million kg of CO₂ (by an offsetting equal amount of gas source). Further, suppose the full potential of 20,000 MWt of direct-use geothermal energy was developed. In that case, gas imports could be reduced by 36%, thereby saving CO₂ emissions of 15.6 million t/year adding USD 618 million / year to the economy of the country (Baba et al., 2021). This thermal energy greatly helps the tourism industry and aid in further reducing 135 million tons of CO₂ (Katircioglu, 2014; WTTC, 2018). The government has realized the potential of geothermal energy as a primary source mix of energy (including for power generation, heating, and the agricultural sector) and is expecting a growth of 61% in the coming decade supported by financial incentives (IEA, 2021c). In such a case, there is no

necessity to implement new policy instruments like the carbon tax, energy efficiency methods, etc., as proposed by Yelden and Voyvoda (2015) to reduce CO₂ emissions and reduce gas imports. Unlocking the EGS potential from the high heat generating granites of western Anatolia will not only maintain sustainable economic growth but also reduce CO₂ emissions. For example, 10 km thick Kestonbol granite pluton with its minimum area of 220 km² (see **Figure 7**), with its average heat production capacity of 7 μW/m³ (Table 2), can generate 176\ billion kWh of electricity. Similarly, a 10 km thick Kozak pluton with an average heat generation capacity of 7 μW/m³, can generate 658 billion kWh of electricity. Thus the granites plutons of western Anatolia with an area of 4221 km² can generate 4 billion MWh of electricity for 30 years. This amount is greater than the current annual energy requirement of 384 billion kWh. Extracting half the available energy from EGS is sufficient for Turkey to bend the carbon index curve towards 2D (circle in Figure 1) and comply with the carbon reduction commitment by CoP in the Paris 2015 agreement.

Turkey's energy targets set for the period 2019 to 2023 includes (IEA, 2021c), a) reduction of natural gas for electricity production from 29.9 to 20.7 %, b) increasing the share of renewable energy sources in electricity production from 32.5 to 38.8%, c) increasing the electricity production from local energy sources from 150 TWh to 219 TWh, d) increasing the primary energy usage from 1.81 to 2.01 toe e) increasing the electricity usage per capita from 3.7 MWh to 4.3 MWh. These energy targets by the country can be achieved by major contribution by hydrothermal and EGS energy sources as primary energy source mix for generating electricity as well as for providing heat.

With the development of new drilling technologies to create heat exchangers in these granites, the levelised cost of power (LCOP) and heat from the granites will be affordable by

the country. The levelised cost of power (LCOP), projected by Sanyal et al. (2007), Sanyal (2009), before the commencement of the Soultz Forte in France and the Cooper Basin, Australia EGS projects, was 5.43 US Cents/KWh. This LCOP is based on models incorporating sensitivity parameters, cost of drilling, temperature resources, and flow rates, and reservoir volumes. Subsequently, field-based measurements obtained from the EGS projects from Soultz Forte in France and the Cooper Basin, Australia could give real LCOP from EGS projects. Thus the proposed feed-in tariff from Soultz Forte is 24 Euro cents /kWh. These costs are based on actual costs incurred in various steps in realizing the EGS project. However, the Govt of France is negotiating a tariff of 12 Euro cents /KWh (Genter et al., 2010; Koelbel and Genter, 2017). However, the LCOP proposed by the Cooper Basin EGS project is shown in **Figure 8**. This is quite logical since this cost is based on the heat flow values and the heat generation of the reservoir sources (granites).

Figure 8. Levelised cost of power from EGS source (adopted from Cooper et al., 2010)

Considering the heat flow values and the geothermal gradients and the heat generation values of the granite batholiths of western Anatolia (heat flow 133 mW/m^2 and temperature resource of 220°C) LCOP from these granites can be < 6 Euro cents/kWh. The heat flow values and the resource temperature of Kestanol and Kozak batholiths are higher compared to the EGS

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4 483 sites in Soultz Forte and Cooper Basin. Further, due to the tectonic configuration of the
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6 484 western Anatolian region, the depth of the resources is shallow. Currently, the cost of heat
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8 485 from hydrothermal sources in Turkey is around 0.45 TL/h (Baba et al., 2021). With
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10 486 government incentives, this cost can be brought down to match the current cost of electricity
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12 487 from hydrothermal sources. Although the ARIMA model project increases renewable by 23
13
14 488 Mtoe by 2040 (Ozturk and Ozturk, 2018), according to the currently available data,
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16 489 renewables will cross this value by 2030 (Table 1). With the development of EGS, the
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18 490 contribution of geothermal energy to the primary source mix will surpass other sources of
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20 491 renewable sources like solar and wind.
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24 492 EGS sources are available in several countries around the RED Sea. Thus Egypt, Yemen
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26 493 Saudi Arabia, Djibouti and Ethiopia and Eritrea have considerable high heat generating
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28 494 granites (Chandrasekharam et al., 2016). These developing countries that need food and
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30 495 water security can adopt the EGS technology for socio-economic growth. Since EGS is not
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32 496 site specific unlike hydrothermal systems, with the development of drilling technology,
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34 497 countries can be energy independent and thus contribute to global carbon dioxide reduction
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36 498 mission in future (MIT, 2016).
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41 42 500 **7. Conclusions**

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44 501 Turkey has a huge primary energy source locked up in its high heat generating granites of
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46 502 western Anatolia, spread over an area (surface area) of 4221 sq.km. Since these are
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48 503 batholiths, their depth extends to several kilometers. Even 2% of energy extracted from these
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50 504 granites can provide base-load electricity and heat to the country, thereby drastically reducing
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52 505 dependency on imported gas and oil and maintain CO₂ emissions to the year 2000 level. The
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54 506 carbon intensity index can be brought close to the 2D scenario, and the country can be
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56 507 economically benefited from the carbon savings. With the successful completion of three
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EGS projects, the technological development of EGS technology would make energy from EGS sources economically viable. The Levelised cost of electricity and heat can be brought down below the current price and estimates. This review demonstrates that besides electricity and heat, EGS can be utilized, together with other renewable energy sources like hydrothermal, wind, and concentrated solar for providing fresh water through the desalination process. These energy sources would provide food, energy, and water security to the country for several decades.

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